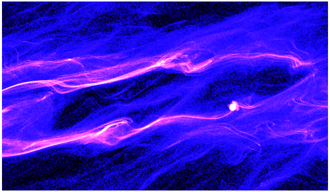
The challenge of radial drift – saving the building blocks of planets



Anders Johansen (Sterrewacht Leiden)

"Planet Formation Processes and the Development of Prebiotic Environments"

Pasadena, March 2008

Collaborators: MPIA: Hubert Klahr, Thomas Henning, Kees Dullemond, Frithjof Brauer, Andrej Bicanski, Andrew Youdin (CITA), Jeff Oishi (AMNH), Mordecai-Mark Mac Low (AMNH), Wladimir Lyra (Uppsala)

Planetesimals

- *Hypothesised* kilometer-sized objects massive enough to attract each other by gravity (two-body encounters)
- Building blocks of planets
- Formation:
  - μm $\rightarrow$ cm: Dust grains collide and stick

    (Blum & Wurm 2000)
  - cm $\rightarrow$ km: Sticking or gravitational instability

    (Safronov 1969, Goldreich & Ward 1973, Weidenschilling & Cuzzi 1993)
- Dynamics of turbulent gas important for modelling dust grains and boulders

William K. Hartmann

Particle dynamics

Gas accelerates solid particles through drag force:

$$\frac{\partial \mathbf{w}}{\partial t} = \ldots - \frac{1}{\tau_{\mathrm{f}}}(\mathbf{w} - \mathbf{u})$$

Particle velocity   Gas velocity

In the Epstein drag force regime, when the particle is much smaller than the mean free path of the gas molecules, the friction time is (Weidenschilling 1977)

$$\tau_{\mathrm{f}} = \frac{a_\bullet \rho_\bullet}{c_{\mathrm{s}} \rho_{\mathrm{g}}}$$

$a_\bullet$: Particle radius

$\rho_\bullet$: Material density

c_{s}: Sound speed

ρ_{g}: Gas density

Important nondimensional parameter in protoplanetary discs:

$\Omega_{\mathrm{K}} \tau_{\mathrm{f}}$ (*Stokes number*)

At $r = 5$ AU we can approximately write $a_\bullet/\mathrm{m} \sim \Omega_{\mathrm{K}} \tau_{\mathrm{f}}$.

Sub-Keplerian rotation

Equilibrium between gravity and radial pressure force:

$$0 = \frac{v_{\rm gas}^2}{r} - \frac{v_{\rm Kep}^2}{r} - \frac{1}{\rho}\frac{\partial P}{\partial r}$$

Define the pressure support parameter

$$\eta = -\frac{\text{Radial pressure gradient}}{2 \times \text{Radial gravity}} = -\frac{\partial P/\partial r}{2\rho v_{\rm Kep}^2/r}$$

Divide equation of motion by radial gravity:

$$0 = \frac{v_{\rm gas}^2}{v_{\rm Kep}^2} - 1 + 2\eta$$

The sub-Keplerian orbital speed of the gas is finally

$$v_{\rm gas} = v_{\rm Kep}\sqrt{1-2\eta} \approx v_{\rm Kep}(1-\eta)$$

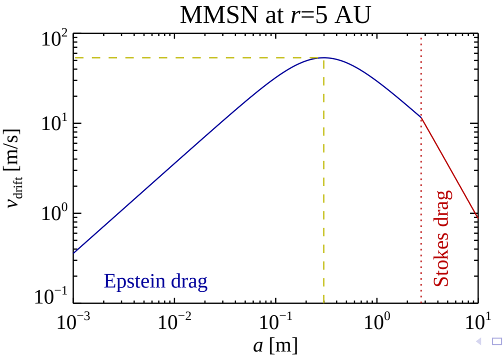
(Weidenschilling 1977; Nagakawa, Sekiya, & Hayashi 1986).

Radial drift

Balance between drag force and head wind gives radial drift speed (Weidenschilling 1977)

$$v_{\rm drift} = -\frac{2}{\Omega_{\rm K}\tau_{\rm f} + (\Omega_{\rm K}\tau_{\rm f})^{-1}}\eta v_{\rm K}$$

for Epstein drag law (solids smaller than gas mean free path).



- MMSN η from Cuzzi et al. 1993
- Maximum drift speed of 50 m/s
- Fastest drifting solids are 30 cm in radius

Why is radial drift important

The radial drift time-scale $t_{\rm drift} \sim r/v_{\rm drift}$:

$$\Omega_{\rm K} t_{\rm drift} \sim \frac{1}{(H/r)^2} \frac{1}{|\partial \ln P/\partial \ln r|}$$

Note: Ignored radial dependence of drift speed and transition to Stokes regime.

- Radial drift time-scale is on the order 50-100 local orbits

Relevance for planetesimal formation theory:

- Solids must grow past the meter barrier faster than radial drift time-scale
- Differential radial drift gives high collision speeds and high random speeds – problem for both coagulation and self-gravity
- Boulders must penetrate to large enough sizes that self-gravity is important
- Short cut: gravitational instability of mm-sized solids?

(Goldreich & Ward 1973, Youdin & Shu 2002, Youdin 2005)

Survival of dust pebbles

- A huge population of pebbles (mm-cm) observed in T Tauri discs at $r \sim 100$ AU

  (Wilner et al. 2000; Testi et al. 2003; Rodmann et al. 2006; Lommen et al. 2007)

- But radial drift should empty outer disc on much shorter time-scale

  (Takeuchi & Lin 2002, Brauer et al. 2007)

- Survival of the observed pebble population can be seen as a proxy for the drift of meter-sized boulders in planet forming regions (Brauer et al. 2007)

How do we live with radial drift?

Overview of talk:

- Reduced radial drift in radial pressure bumps
  - Pressure bumps form in magnetorotational turbulence
  - Anticyclonic gas flow collect boulders
- Reduced radial drift in self-shielding particle clumps
  - Streaming instability
  - Interaction of streaming and Kelvin-Helmholtz instabilities
- Jump over the meter barrier by self-gravity
  - Kitchen sink simulation of planetesimal formation
- Conclusions and future challenges

How do we live with radial drift?

Overview of talk:

- Reduced radial drift in radial pressure bumps
  - Pressure bumps form in magnetorotational turbulence
  - Anticyclonic gas flow collect boulders
- Reduced radial drift in self-shielding particle clumps
  - Streaming instability
  - Interaction of streaming and Kelvin-Helmholtz instabilities
- Jump over the meter barrier by self-gravity
  - Kitchen sink simulation of planetesimal formation
- Conclusions and future challenges

Will *not* talk about:

- Efficient coagulation over the meter barrier

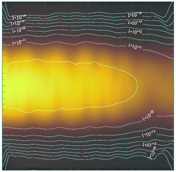
(Weidenschilling 1997, Dullemond & Dominik 2005, Brauer et al. 2008, Jürgen Blum's talk)

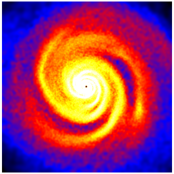
Dust in turbulence

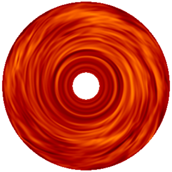
Solid particles are moved around by the turbulent gas in the protoplanetary disk.

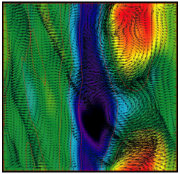
Sources of turbulence:

- Convection (Lin & Papaloizou 1980; Klahr et al. 1999)
- Self-gravity (Toomre 1964; Gammie 2001; Rice et al. 2005)
- Magnetic fields (Balbus & Hawley 1991)
- Baroclinic conditions (Klahr & Bodenheimer 2003)
- . . .



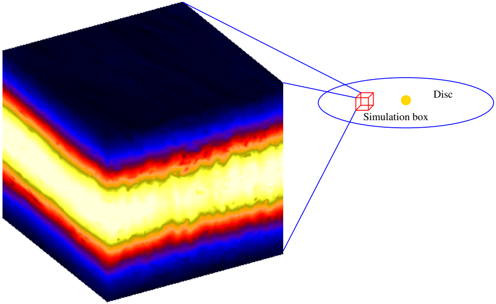






Magnetorotational turbulence

Magnetorotational instability is a robust source of turbulence and accretion in protoplanetary discs with a sufficient degree of ionization (Balbus & Hawley 1991, talks by Desch and Salmeron yesterday).



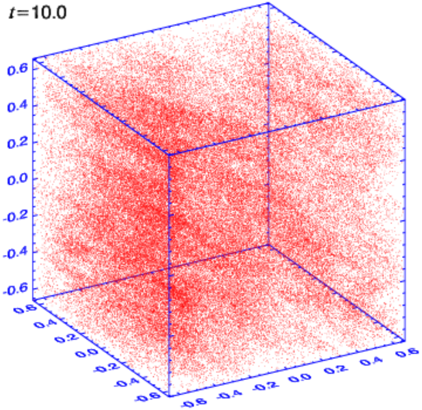
Shearing box

Code: The Pencil Code (Brandenburg 2003)

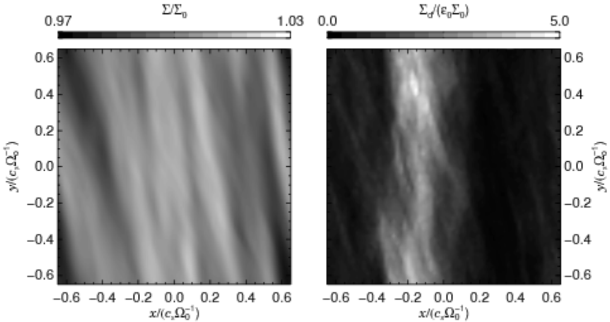
[MHD code, finite differences, 6th order in space, 3rd order in time]

Particle concentrations

Johansen, Klahr, & Henning (2006):
2×10^6 m-sized solid particles in magnetorotational turbulence.



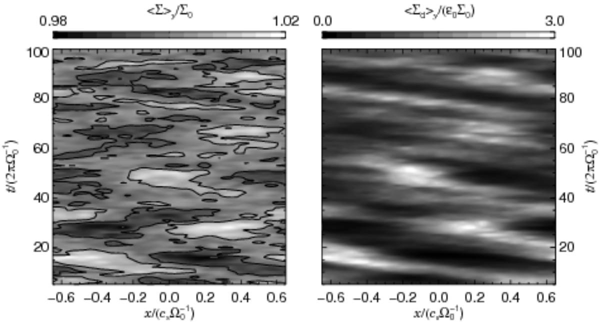
Gas density bumps



- Strong correlation between high gas density and high particle density.
- Solid particles are caught in gas overdensities

  (Whipple 1972, Klahr & Lin 2001, Haghighipour & Boss 2003)
- Gravoturbulent formation of planetesimals

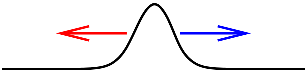
Gas density bumps



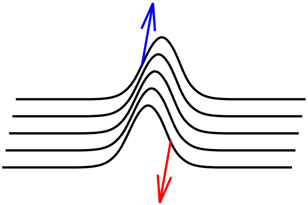
- Strong correlation between high gas density and high particle density.
- Solid particles are caught in gas overdensities

  (Whipple 1972, Klahr & Lin 2001, Haghighipour & Boss 2003)
- Gravoturbulent formation of planetesimals

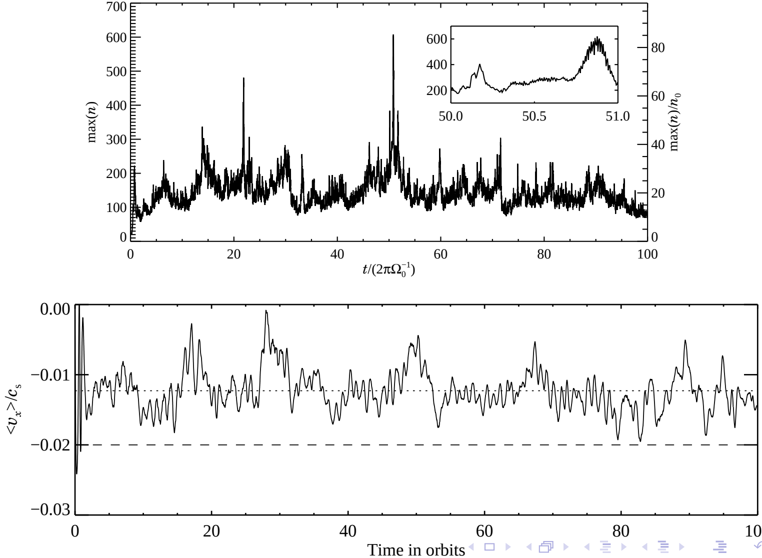
Pressure gradient trapping



- Outer edge:
  Gas sub-Keplerian. Particles forced by gas drag to move inwards.
- Inner edge:
  Gas super-Keplerian. Particles forced by gas drag to move outwards.

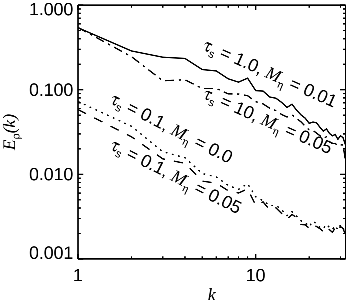


Maximum density/radial drift



Clumping statistics

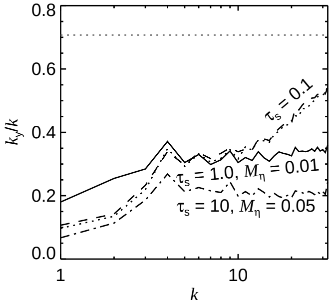
Shell-integrated, normalized particle density spectrum as a function of wavenumber $k = \sqrt{k_x^2 + k_y^2}$:



- Concentrations are driven by the largest scales of the box
- $k = 1$ scale has concentration comparable to average density
- Youdin & Johansen (in preparation)

Anisotropic clumping

Typical azimuthal wavenumber k_y as a function of total wavenumber k:



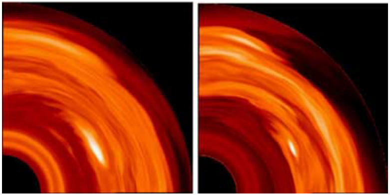
- Large scale concentrations are predominantly radial
- More isotropic concentration at smaller scales
- Anticyclonic regions and zonal flows main concentration agents
- Youdin & Johansen (in preparation)

Global models

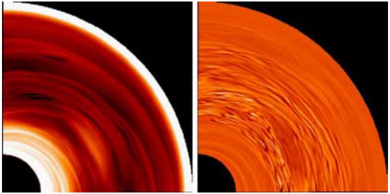
Fromang & Nelson (2005):

Boulders concentrate in long-lived vortex in MRI turbulence.

Dust density (5 cm and 25 cm):



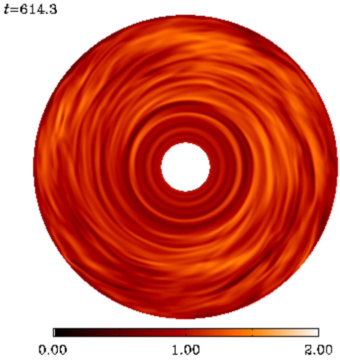
Gas density and vorticity (ω_z):



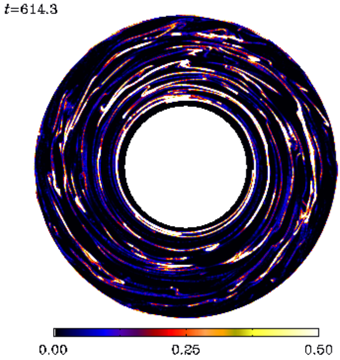
Global models

Lyra, Johansen, Klahr, & Piskunov (2008):

- Global disc with boulders on Cartesian grid (disk-in-a-box)

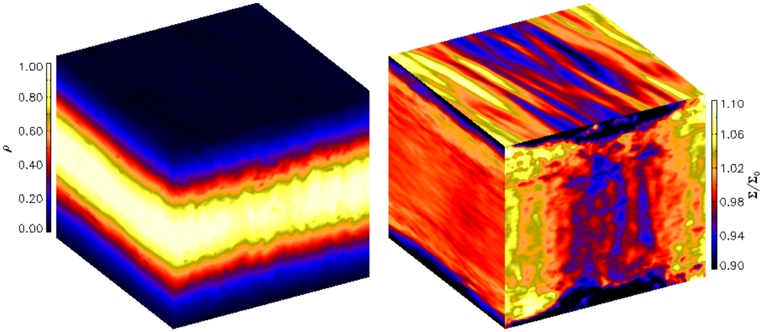


Gas density ($320 \times 320 \times 32$)



Particle density (10^6 particles)

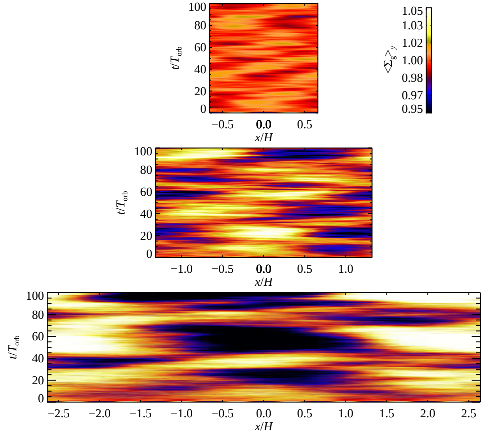
Box size matters



- Box size of $(5.28H)^3$
- Vertically extended density “pillars” (Taylor-Proudman)
- Surrounded by zonal flows
- Inverse cascade or directly caused by MRI?
- Johansen, Klahr, & Youdin (in preparation)

Box size matters

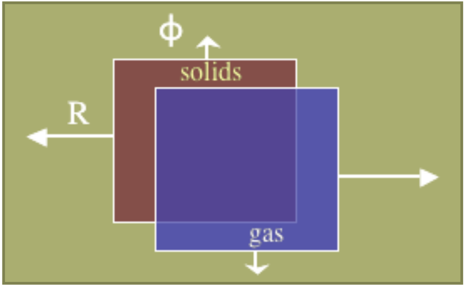
- Stratified shearing sheet simulations with increasing box size



- Density amplitude $\hat{\rho}(k_x) \propto k_x^{-2}$
- Life-time of high pressure bumps increases with box size

Streaming instability

Youdin & Goodman (2005) :
"Streaming Instabilities in Protoplanetary Disks"

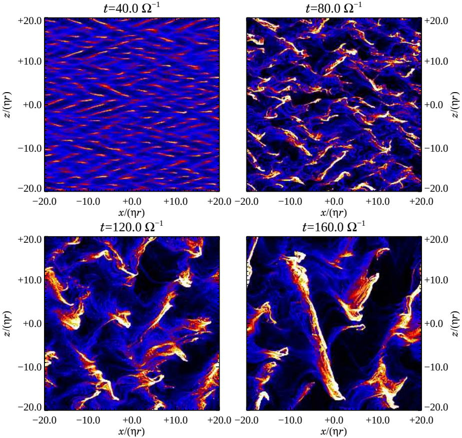


The "traffic jam" view of the streaming instability:

- Regions with slightly more solids have less radial drift
- Lower density material piles up from upstream, increasing local solids-to-gas ratio

Streaming instability movie

Linear and non-linear evolution of radial drift flow of meter-sized boulders ($\Omega_K \tau_f = 1$):

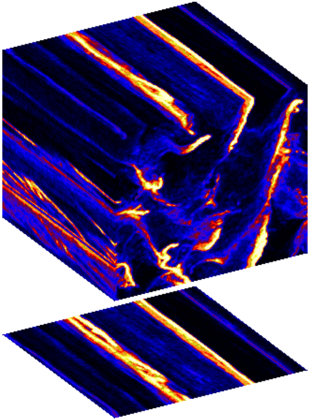


The radial drift flow of solids is linearly unstable!

(Youdin & Johansen 2007, Johansen & Youdin 2007)

Streaming instability 3-D

Grid resolution of 128^3, with 20,000,000 superparticles:

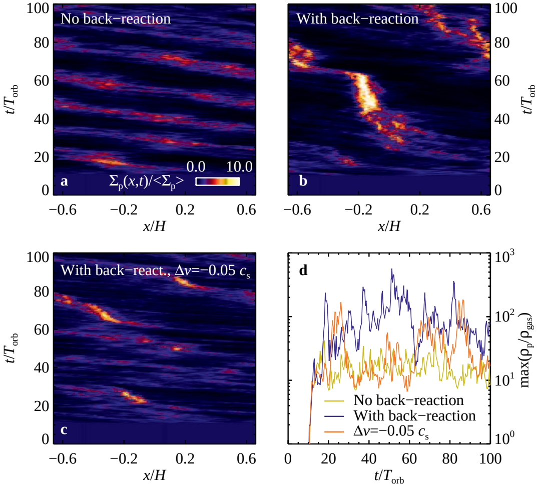


Particle size:

1 m @ 5 AU or 1 cm @ 40 AU

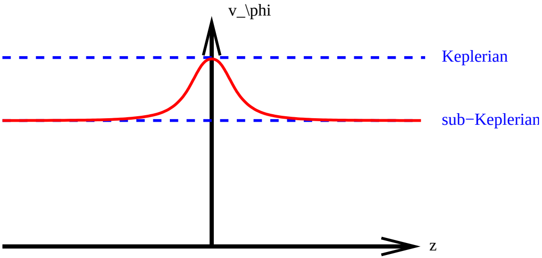
The turbulent diffusion coefficient of the flow is $\delta_t = 0.02$ and the Mach number Ma$= 0.05$. Comparable in strength to MRI turbulence, but α-value negative!

Sedimentation in magnetised turbulence



- Streaming instability and pressure bump concentration interact constructively

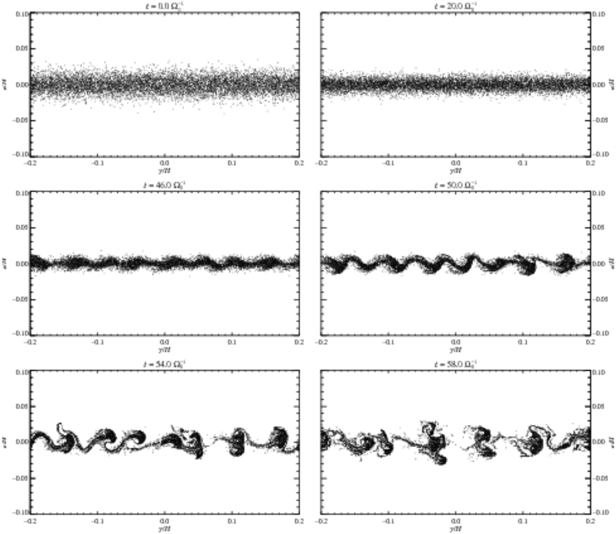
Kelvin-Helmholtz instability



- Gas forced to move sub-Keplerian away from the mid-plane (by the global pressure gradient) and Keplerian in the mid-plane (by the particles)
- Vertical shear is unstable to Kelvin-Helmholtz instability
- Subsequent turbulence lifts up the particle layer and reduces the particle density in the mid-plane

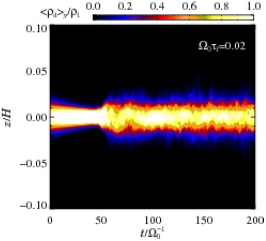
Kelvin-Helmholtz simulations

Johansen, Henning, & Klahr (2006)

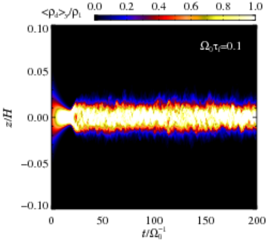


Particle density

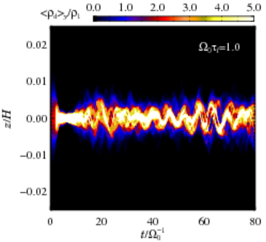
Pebbles (cm)



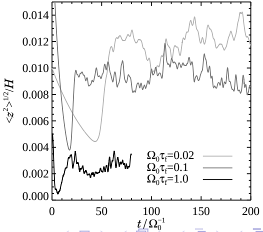
Rocks (dm)



Boulders (m)

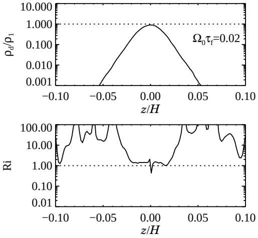


Scale height vs. t

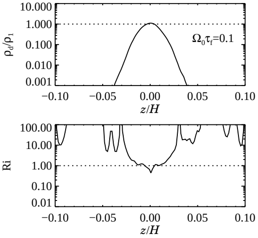


Average density

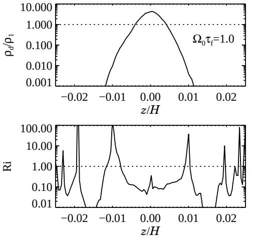
Pebbles

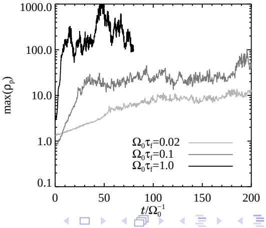


Rocks



Boulders

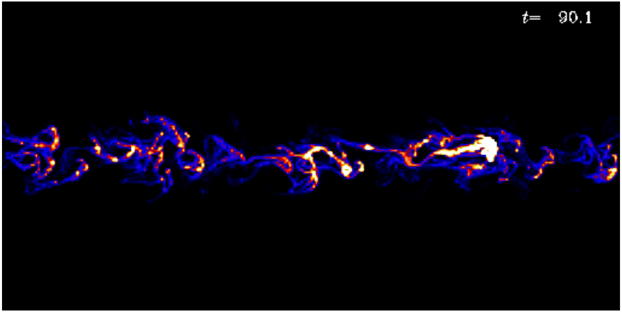




Clumping movie

Particle density contours of dm-sized rocks:

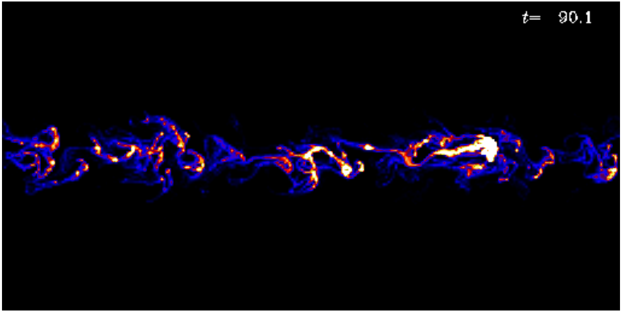
(black=no particles, blue=few particles, bright=lots of particles):



sub-Keplerian flow

Clumping movie

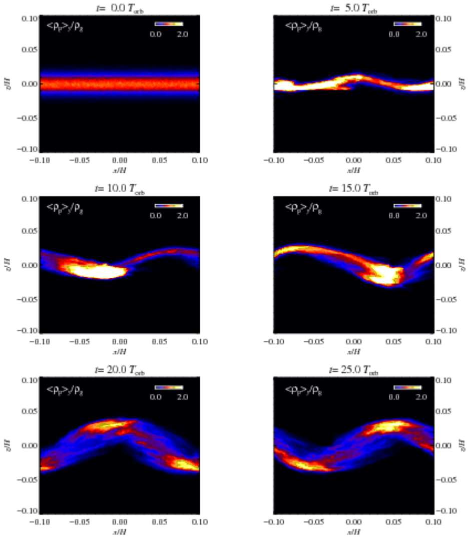
Particle density contours of dm-sized rocks:
(black=no particles, blue=few particles, bright=lots of particles):



sub-Keplerian flow

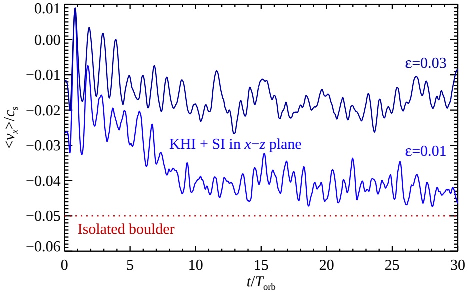
- The particle density is very non-axisymmetric.

Sedimentation in the x-z plane



Sedimentation in the x-z plane

Radial drift speed of $\Omega_{\rm K}\tau_{\rm f} = 1$ particles for two different values of the solids-to-gas ratio ϵ:

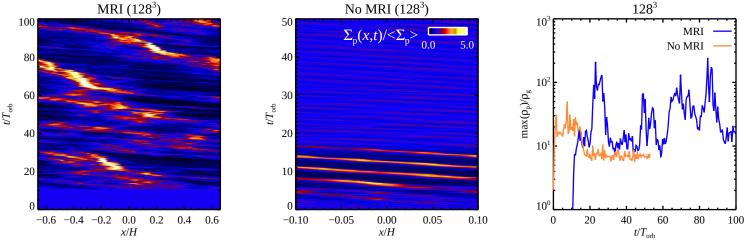


- The standing wave has so modest overdensities that radial drift almost equal to that of an isolated boulder
- Dense clumps form again for $\epsilon = 0.03$
- Particle pile-ups and photoevaporation of gas can increase solids-to-gas ratio locally

(Youdin & Shu 2002, Throop & Bally 2005, Alexander & Armitage 2007)

MRI+SI versus SI alone

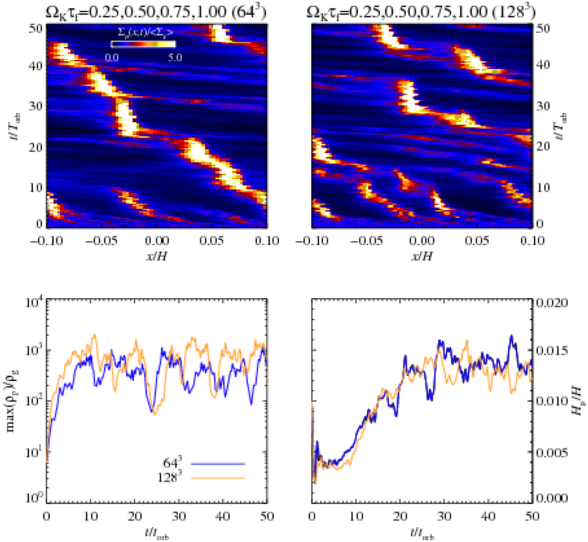
- Left plot: boulder column density versus x and time t for simulation with magnetic fields and two-way drag forces
- Middle plot: same, but for simulation with two-way drag forces and no magnetic field
- Right plot: the maximum particle density versus time



- MRI and SI interact constructively

MRI+SI versus SI alone

Long-lived particle clumps return at $\epsilon = 0.03$:



Self-gravity

New term in equation of motion of the particles:

$$\frac{\mathrm{d}\mathbf{v}_i}{\mathrm{d}t} = \ldots - \boldsymbol{\nabla}\Phi_{\rm self}$$

The gravitational potential of the particles $\Phi_{\rm self}$ is found by solving the Poisson equation

$$\nabla^2\Phi_{\rm self} = 4\pi G\rho_{\rm par}$$

We have developed a fully parallel shearing sheet Poisson solver. Technical details:

- Solids are treated as particles
- Gravity potential of solids found on mesh using FFT method (Gammie 2001)
- Triangular Shaped Cloud assignment/interpolation scheme (Hockney & Eastwood 1981, Youdin & Johansen 2007)
- Much faster than direct summation, but resolution limited by mesh

Collaboration with Jeff Oishi and Mordecai Mac Low at the American Museum of Natural History in New York.

The "kitchen sink" simulation

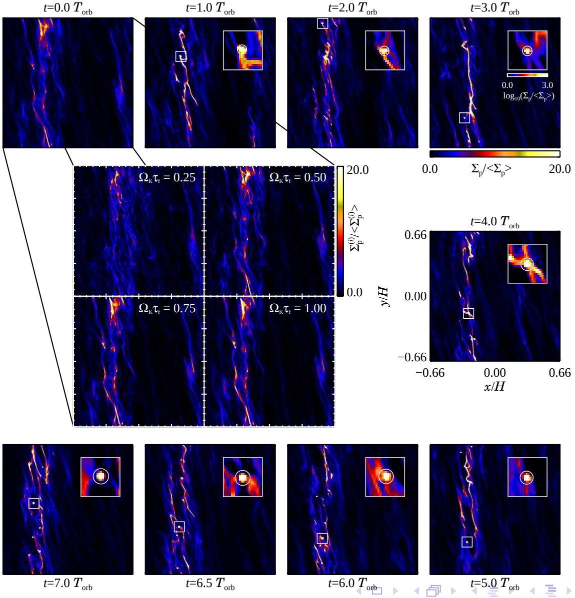
Combine known effects (but never studied together):

- Magnetorotational turbulence (256^3 grid points)
- Sedimentation (8,000,000 superparticles)
- Concentrations in transient high pressure regions
- Streaming instability

with some new physics:

- Self-gravity of boulders
- Several particle sizes
  Radii from 15 cm to 60 cm
  Differential radial drift of different particle sizes potentially disrupts gravitational collapse (Weidenschilling 1995)
- Collisional cooling
  Collisions between boulders dynamically important for solids-to-gas ratio $\gtrsim 10 \ldots 100$.
  Collisions are highly inelastic $\Rightarrow$ local rms speed of particles damped on collisional time-scale

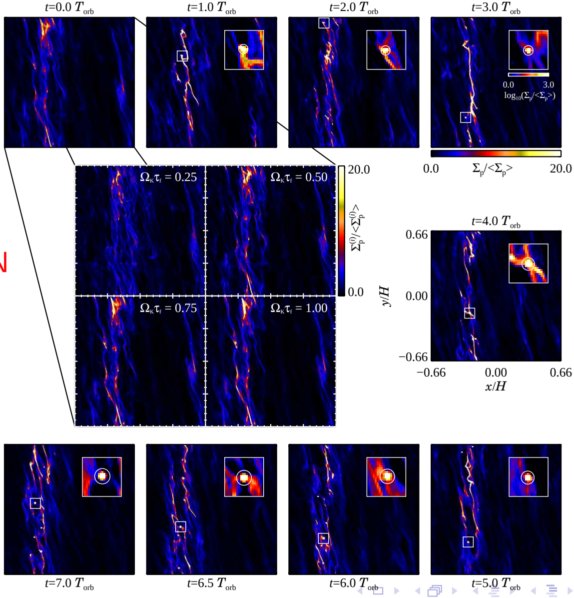
Clump condensation



Clump condensation

$2 \times$ MMSN

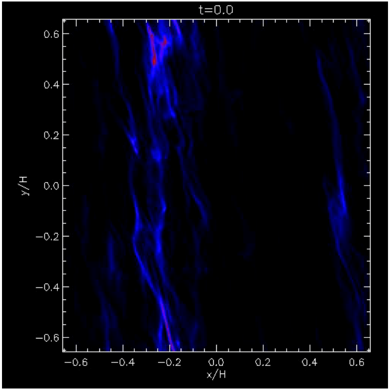
$\epsilon = 0.01$



Planetesimal formation movie

Time is in Keplerian orbits (1 orbit $\approx$ 10 years)

Keplerian flow

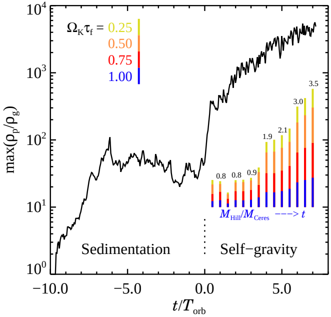


Keplerian flow

Johansen et al. 2007 (Nature, 448, 1022)

Accretion

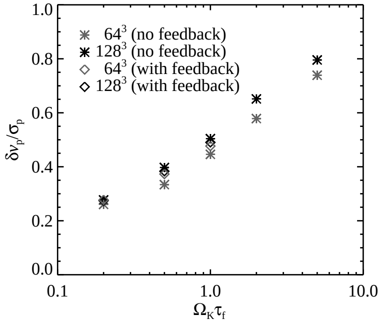
- Turbulent concentrations and streaming instability interact constructively and produce overdensities of several 100 in the mid-plane layer
- Gravitationally bound clumps condense out even in discs comparable to the minimum mass solar nebula.
- Differential radial drift of different particle sizes does not disrupt the collapse
- Clumps have masses similar to dwarf planets and continue to accrete.



- Growth from boulders to planetesimals does not rely on sticking efficiency.
- Collapse happens much faster than the radial drift time-scale.

Collisional fragmentation

- What about collisional fragmentation?
  - Typical collision speeds of 5-10 m/s
  - Back-reaction drag force reduces turbulent collision speeds in the mid-plane by up to 30–40%
  - Collision speeds may be underestimated due to underresolvement of turbulent scales that induce collisions



- PhD project of Andrej Bicanski in Heidelberg
- See also Carballido, Stone, & Turner (2008)

Conclusions

- Radial drift is a major challenge for planetesimal formation theory

But:

- Radial drift is reduced in pressure bumps that arise spontaneously in MRI turbulence
- Dense particle clumps may locally turn off gaseous head wind (streaming instability), reducing radial drift even more
- Streaming and Kelvin-Helmholtz instabilities in isolation may puff up mid-plane so that overdensities are very modes, unless solids-to-gas ratio is (somewhat) increased
- Pressure bumps from MRI turbulence can tame the streaming instability and lead to very high concentrations
- Formation of 1000 km planetesimal by self-gravity

Future challenges

- High resolution measurements of boulder collisions
- Better understanding of zonal flows and vortices in magnetorotational turbulence
- Global models of the streaming instability
- Dead zone models (with Chao-Chin Yang and Mordecai Mac Low at AMNH)
- Pushing towards smaller particle sizes
- Include collisional fragmentation
- Initial mass function of clumps
- Long-term evolution including hierarchical fragmentation into smaller planetesimals
- How do you create boulders in the first place?